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Testing the timing of radiocarbon-dated events between proxy archives

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Abstract: For interpreting past changes on a regional or global scale, the timings of proxy-inferred events are usually aligned with data from other locations. However, too often chronological uncertainties are ignored in proxy diagrams and multisite comparisons, making it possible for researchers to fall into the trap of sucking separate events into one illusionary event (or *vice versa*). Here we largely solve this 'suck in and smear syndrome' for radiocarbon (^{14}C) dated sequences. In a Bayesian framework, millions of plausible age-models are constructed to quantify the chronological uncertainties within and between proxy archives. We test the technique on replicated high-resolution ^{14}C-dated peat cores deposited during the 'Little Ice Age' (*c.* AD 1400–1900), a period characterized by abrupt climate changes and severe ^{14}C calibration problems. Owing to internal variability in proxy data and uncertainties in age-models, these (and possibly many more) archives are not consistent in recording decadal climate change. Through explicit statistical tests of palaeoenvironmental hypotheses, we can move forward to systematic interpretations of proxy data. However, chronological uncertainties of non-annually resolved palaeoclimate records are too large for answering decadal timescale questions.

Key words: Bayesian age-modelling, radiocarbon, chronological uncertainty, meta-analysis, synchronicity of events, 'Little Ice Age'.

Introduction

Past environmental change (eg, climate change) is usually inferred from changes in pollen, isotopes and other fossil proxies found in deposits from, for example, lakes, peat bogs, ice sheets or oceans. However, climate change can have a complex spatial pattern, proxy changes can be forced by other factors (eg, human impact, internal processes, measurement errors) and many proxy archives have non-negligible chronological uncertainties. Therefore, even replicate reconstructions within regions often differ considerably in details. This becomes especially problematic when proxy-inferred abrupt climate events such as the last glacial–interglacial transition, '8.2 kyr event' or 'Little Ice Age' are linked between regions (van Geel *et al.*, 1998; Mayewski *et al.*, 2004; Rohling and Pälike, 2005; VanderGoes *et al.*, 2005) or with supposed forcing factors (van Geel *et al.*, 1998; Bond *et al.*, 2001; Neff *et al.*, 2001; Mauquoy *et al.*, 2002b; Blaauw *et al.*, 2004; Magny, 2004; Wang *et al.*, 2005). There have undoubtedly been climate changes of regional or global scale and, at least occasionally, these have been rapid. However, there are also cases where reported synchroneity between archives could have been caused by age-model errors, mistaken interpretations of proxy data, or even by wishful matching (eg, tuning of records, subjectively selecting age-models, neglecting non-responsive sites, or drawing suggestive event-connecting lines: Bond *et al.*, 2001; Neff *et al.*, 2001; cf. Baillie, 1991; Wunsch, 2006).

Chronological problems in ^{14}C-dated sequences arise because (i) owing to constraints in budget, time and dateable material, not every level or event can be dated, necessitating some kind of estimation for non-dated levels (Bennett, 1994;

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Bennett and Fuller, 2002; Telford *et al.*, 2004a; Blaauw and Christen, 2005; Heegaard *et al.*, 2005), (ii) ^{14}C dates have associated measurement uncertainties, (iii) ^{14}C dates could be offset, inaccurate or outlying (Blaauw *et al.*, 2005), and (iv) after calibration, ^{14}C dates often obtain a multimodal calibrated distribution without an obvious best point estimate for its calendar age (Telford *et al.*, 2004b). Even with many data and sophisticated models, accumulation histories (changes in accumulation rate, hiatuses) of non-annually layered deposits will thus never be known exactly. This is especially true for periods such as during the past four centuries where the ^{14}C calibration curve shows major wiggles, resulting in exceptionally problematic age-models. Many proxy archives apparently register climate change during such periods (van Geel *et al.*, 1998; Mauquoy *et al.*, 2002a,b; Soon and Baliunas, 2003; Mayewski *et al.*, 2004; Rohling and Pälike, 2005), further enlarging the danger of 'suck-in and smear' (Baillie, 1991).

Although statistical methods exist to estimate uncertainties of ^{14}C age-models (Bennett, 1994; Bennett and Fuller, 2002; Blaauw and Christen, 2005; Heegaard *et al.*, 2005), there has hitherto been no method that can translate these uncertainties to display graphically the chronological uncertainty of the proxy values (van Geel *et al.*, 1998; Bond *et al.*, 2001; Mauquoy *et al.*, 2002a,b; Hu *et al.*, 2003; Blaauw *et al.*, 2004; Rohling and Pälike, 2005; VanderGoes *et al.*, 2005; Wang *et al.,* 2005). This is because generally a single age–depth curve is used to translate core depths into point estimates of calendar ages, resulting in line-graphs which falsely suggest that the timing of changes is known exactly (even where it is known that this is not the case).

Raised bog deposits are regularly used for reconstructing Holocene climate changes in temperate regions (Mauquoy *et al.*, 2002a,b; Blaauw *et al.*, 2004; Charman *et al.*, 2004). Raised bog surfaces consist of dry hummocks, intermediate lawns and wet hollows or pools, each having their characteristic moisture-sensitive vegetation. As raised bogs depend entirely on precipitation for their water and nutrients, climate change should affect their vegetation composition. Increased precipitation or lower temperatures would lead to a higher water-table and thus to the extension of wet and moist microforms (wet-shift) (Mauquoy *et al.*, 2002b; Blaauw *et al.*, 2004; Charman *et al.*, 2004). As inception dates for dry-shifts are more difficult to pinpoint, we will limit our focus to clearly registered wet-shifts and will thus reconstruct events of climatic cooling/moistening only.

Methods

Bayesian statistics combines new data with prior observations in order to infer the probability that a hypothesis may be true. When Bayesian statistics is applied to age-modelling, chronological uncertainties of high-resolution ^{14}C-dated sequences can be much reduced, because the calibrated ages of individual ^{14}C dates become constrained by prior assumptions and by all other ^{14}C dates in a sequence. Here we fit the sequences of uncalibrated ^{14}C dates from raised bog peat cores from Denmark (Lille Vildmose, core LVM; Mauquoy *et al.*, 2002a,b) and England (Walton Moss, replicate cores WLM19, WLM20 and WLM21; Mauquoy *et al.*, 2002a,b) to the IntCal04 calibration curve (Reimer *et al.*, 2004) assuming piece-wise linear accumulation of the peat deposits (wiggle-match dating; Blaauw and Christen, 2005). Our assumptions are: (i) all cores are divided into three sections, with each section having accumulated linearly (the same number of sections was used for the WLM cores by Mauquoy *et al.* 2002a,b. Using three sections, section breaks often coincided with vegetation composition changes, and the fit F was satisfactory; Blaauw and Christen, 2005); (ii) fresh bogs accumulate at 10 ± 5 cm/yr (AlphaMean 10, AlphaStd 5, see figure 3a in Blaauw and Christen, 2005), (iii) hiatus lengths are very short (HiatusA: 0.0005, HiatusB: 0.005. These parameters shape the prior distribution, see figure 3b in Blaauw and Christen, 2005); (iv) prior outlier probabilities of ^{14}C dates are 5%; (v) a weak dependency of accumulation rates exists between sections; (vi) as historically anchored pollen evidence shows that the upper ^{14}C-dated levels in the four cores should be older than AD 1850 (Mauquoy *et al.*, 2002a), the upper allowed ages are restricted to 100 cal. BP (where BP = before AD 1950).

Under the above assumptions the posterior distributions of many parameters are estimated through several hundreds of millions of Markov Chain Monte Carlo (MCMC) iterations (Blaauw and Christen, 2005), where every iteration may be regarded as a simulation of the corresponding (posterior) probability distribution of all parameters. Chronological uncertainties become especially large in core WLM20 where a hiatus was inferred. Inferred levels of accumulation rate change often coincide with notable changes from long-lasting dry to consistently wetter and more variable conditions (confirming accumulation rate changes). We develop grey-scale proxy graphs based on millions of Bayesian 'wiggle-match' age-models (Blaauw and Christen, 2005; Figures 1 and 2), which convey the important message that even high-precision dated proxy archives possess inherent chronological uncertainties. Here instead of plotting *depth* against calendar age, we plot the *proxy values* obtained at the depths against calendar age. Wide light-grey areas warn us of high chronological uncertainty, while narrow dark areas indicate more secure sections in chronologies.

The MCMC calendar age estimates obtained for the depths in a sequence, can be used to calculate the probabilities of wet-shifts over time. First we define the probability of a wet-shift event in a single core during a certain period of time as $p(W_{ymax,\ ymin})$, where W is the wet-shift event, and y_{max} and y_{min} form the boundaries (in cal. BP years) of the period of interest. Those depths in the core where clear wet-shifts have been found using the macrofossil proxy data are called d_w. For every set of parameters M_i in a MCMC iteration, these depths d_w will be translated into point estimates of their calendar ages, y_w. If in iteration i the estimated calendar age y_w for any of the depths d_w falls within our period of interest ($y_{max}-y_{min}$), this iteration is counted as 'successful' and we assign a 1 to the variable I_i; otherwise I_i becomes 0. We calculate the above for all MCMC iterations and find the proportion of 'successful' iterations. This then forms our estimate of the probability of a wet-shift having taken place in a core during a period of time, $p(W_{ymax,\ ymin})$. $p(W_{ymax,\ ymin})$ can be calculated for specific periods of interest, or repeatedly for an entire core using an appropriate resolution. High values of $p(W_{ymax,\ ymin})$ indicate that a wet-shift likely occurred during the period of interest; low values either indicate the absence of a wet-shift, or lack of information (eg, hiatus). To combine the $p(W_{ymax,\ ymin})$ of multiple cores, we calculate the average of all $p(W_{ymax,\ ymin})$. The methodology for analysing synchronous events in chronologies is not restricted to the particular age-modelling assumptions (here piece-wise linear accumulation), and other age models and accumulation assumptions may be used.

Results and discussion

Many raised bog studies report synchronicity of wet-shifts within sites and regions (Barber *et al.*, 1998; Langdon and Barber, 2005). However, these studies were based on low resolution of analysis and dating, and synchroneity was assessed subjectively (proxy diagrams based on single age-depth curves were aligned by eye). The cores used in this study were analysed and dated at much higher resolution (centimetre-scale macrofossil analysis and >20 ^{14}C dates per core); here the cores are tested systematically for synchroneity of wet-shifts within a given time window. Vegetation composition shows obvious shifts from dry/moist to wetter conditions at 75.5–71.5 and 64.5 cm depth in core LVM, at 74.5–73.5, 54.5 and 45.5 cm in WLM19, at 70.5, 41.5 and 38.5 cm in WLM20, and at 46.5, 44.5 and 42.5–41.5 cm in WLM21 (Mauquoy *et al.*, 2002a). A visual comparison of the four wet-shift chronologies suggests that around *c.* 700, 450 and 350 cal. BP, wet-shifts were synchronous between cores (Figures 2 and 3). However, instead of the usual approach of letting our eyes judge the (a)synchrony of events, we calculate the actual probabilities of specific hypotheses.

Holocene events of sharply increasing atmospheric ^{14}C levels ($\Delta^{14}C$; Reimer *et al.*, 2004) are caused by declines

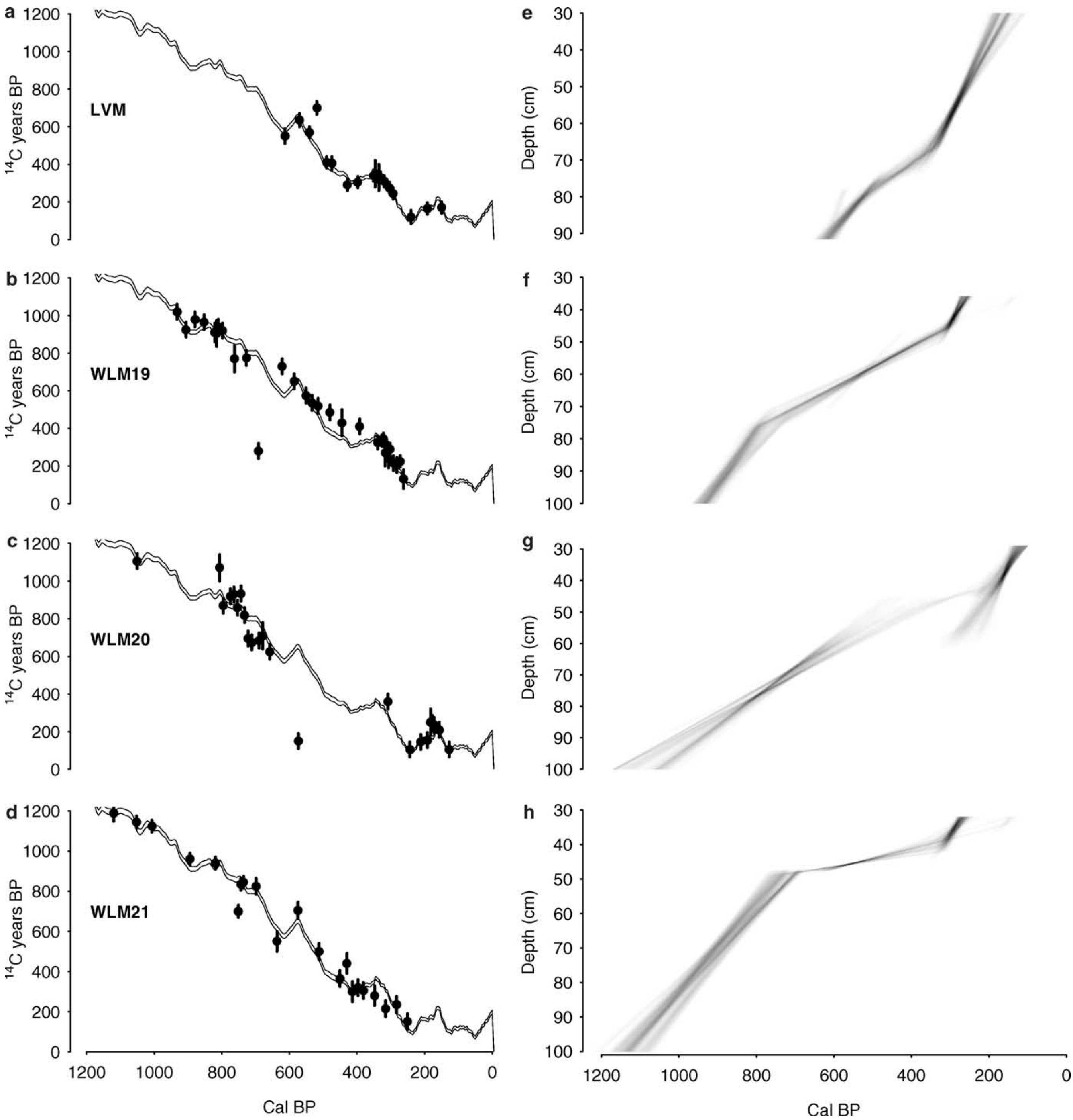

Figure 1 Age-models for core LVM (a,e) and replicate cores WLM19 (b,f), WLM20 (c,g) and WLM21 (d,h) (Mauquoy *et al.*, 2002a,b). a–d, best fits of the ^{14}C sequences to IntCal04 (Reimer *et al.*, 2004) with vertical bars and double lines showing the 1 standard deviation ranges; e–h, age–depth models (grey-scales indicate chronological uncertainty; Blaauw and Christen, 2005) based on divisions into three sections

in solar activity and linked with wet-shifts in northwest European raised bog deposits (van Geel *et al.*, 1998; Mauquoy *et al.*, 2002a,b; Blaauw *et al.*, 2004) and with climate change in several other regions (van Geel *et al.*, 1998; Bond *et al.*, 2001; Magny, 2004; Wang *et al.*, 2005). To the eye, most wet-shifts in our cores appear simultaneous with $\Delta^{14}C$ peaks (Figure 3). However, this apparent synchronicity does not hold when tested in our Bayesian framework (Table 1, Figure 3). Only the Maunder Minimum and the long-lasting Spörer Minimum are accompanied by moderate to high probabilities for wet-shifts (although not for core WLM20). The age-ranges of some wet-shifts appear to overlap with major volcanic eruptions that might have had considerable influence on 'Little Ice Age' climate (Zielinski, 2000). However, when focusing on these short-lived events, probabilities of wet-shifts having occurred within 5 years after major volcanic eruptions (Zielinski, 2000) become even lower (Table 1, Figure 2). Besides assessing synchronicity of short-lived, decadal events, we test whether evidence is found in the cores for regional climate cooling/moistening during any part of the 'Little Ice Age' (*c.* 550 to 50 cal. BP). The probabilities of wet-shifts having occurred during these century-long periods, are 100% for all cores (Table 1).

Our analysis shows that synchronicity of events between proxy archives (van Geel *et al.*, 1998; Mayewski *et al.*, 2004; Rohling and Pälike, 2005; VanderGoes *et al.*, 2005) depends heavily on the assumed length of the event, as should be expected. Moreover, chronological uncertainties of even high-precision ^{14}C age-models (in the best of cases *c*. 30 to 140 calendar years at 95% confidence intervals) prevent the assessment of short timescale events such as volcanic eruptions, and thus force us to limit our resolution to multidecadal or longer lasting events. On centennial timescales probabilities of synchronous reactions become much higher, but in such cases we might well be sucking separate events into one (Baillie, 1991; Soon and Baliunas, 2003). As an alternative to our approach, one could consider events from multiple archives to be synchronous if their age estimates have overlapping confidence intervals. However, in that case comparisons of less precise chronologies would inevitably result in more events being labelled synchronous (with the obvious danger of 'sucking in' separate events). Using our approach, if events are dated at higher precision, truly synchronous events will indeed receive higher probabilities of being identified as such.

The Bayesian methods developed here form an important step towards more systematic assessments of links, leads and lags between different palaeoclimate archives (Baillie, 1991). Although we tested our methods on high-resolution macrofossil archives from 'Little Ice Age' raised-bogs, they are fully applicable to other types of geological archives (dated with ^{14}C or otherwise). Inherent chronological uncertainties need no longer be neglected in proxy-graphs nor in interpretations. Moreover, using proxy information from single cores, or subjectively aligning multiple cores, presents dangers also in many other types of proxy archives. As the palaeoclimate community is increasingly zooming in towards decadal-scale events (van Geel *et al.*, 1998; Bond *et al.*, 2001; Mayewski *et al.*, 2004; Rohling and Pälike, 2005; VanderGoes *et al.*, 2005; Wang *et al.*, 2005), efforts should be increased to acknowledge,

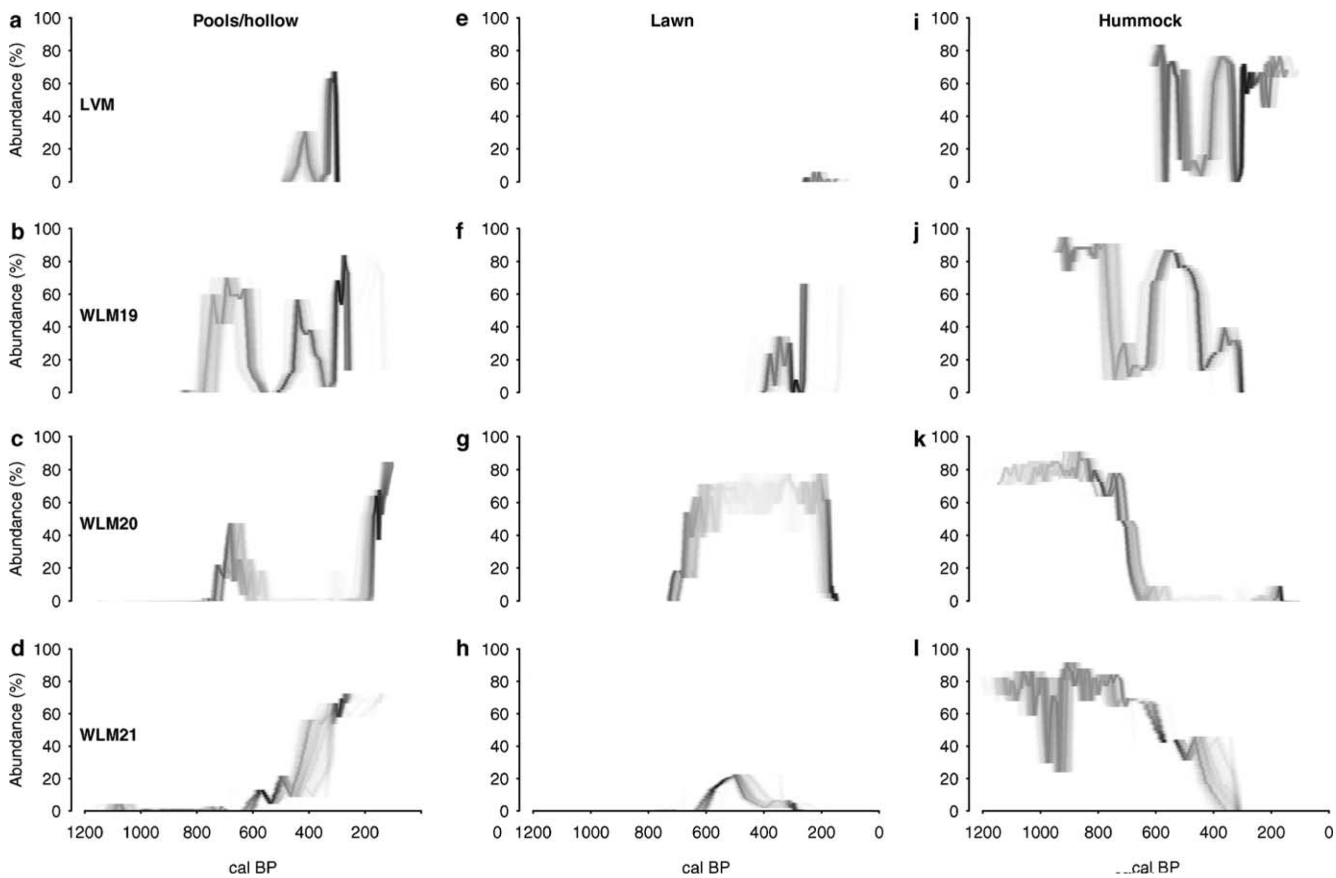

Figure 2 Chronologies of macrofossil-inferred local wetness from core LVM (a,e,i) and replicate cores WLM19 (b,f,j), WLM20 (c,g,k) and WLM21 (d,h,l) (Mauquoy *et al.*, 2002a,b). a–d, combined abundances of pool/hollow species (*Sphagnum cuspidatum*, S. Sect. *Cuspidata* and *S. tenellum*), indicating wet conditions; e–h, combined abundances of lawn species (*S. magellanicum* and *S. papillosum*), indicating intermediate moisture; i–l, combined abundances of hummock species (*S. imbricatum* and *S. capillifolium*), indicating dry conditions

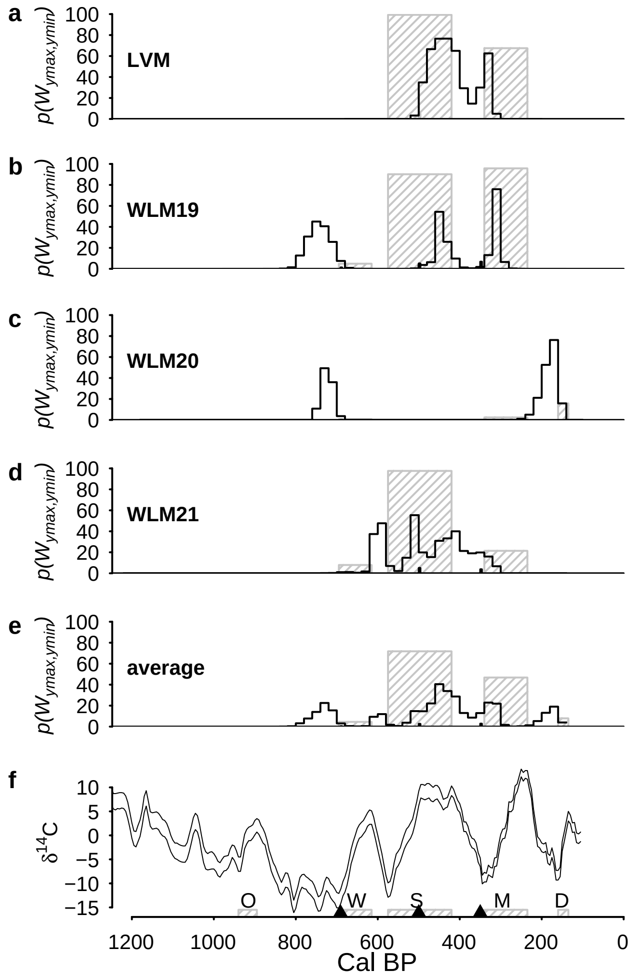

Figure 3 Meta-analysis of wet-shift chronologies in the studied peat cores (Mauquoy *et al.*, 2002a,b), according to a selection of window widths. a, core LVM; b, core WLM19; c, core WLM20; d, core WLM21; e, average for the four cores. Thin lines are consecutive 20 yr bins for $p(W_{y-10,y+10})$ during the past 1200 years. f, thin lines show 1 standard deviation envelope of $\Delta^{14}C$ (Reimer *et al.*, 2004). On the calendar year BP scale, the solar minimum events from Table 1 are plotted as grey dashed rectangles, and the volcanic events as black triangles. O, Oort; W, Wolf; S, Spörer; M, Maunder; D, Dalton. The wet-shift probabilities $p(W_{ymin,ymax})$ for each of these events are plotted as grey and black bins in a–e

quantify and reduce chronological uncertainties of proxy archives. Only with the help of rigorous statistical analyses of proxy data, can the ever-persistent 'suck in and smear' problem be avoided.

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Table 1 Probabilities (%) that wet-shifts occurred in the four studied cores during specific reported events of climate change

Event	Age (cal. BP)	LVM	WLM19	WLM20	WLM21	Mean
Oort[a]	940–895	–[c]	0	0	0	0
Wolf[a]	695–615	–[c]	4.9	0.7	7.9	4.5
Spörer[a]	575–420	99.3	90.2	0	97.6	71.8
Maunder[a]	340–235	67.5	95.8	2.4	21.4	46.8
Dalton[a]	160–135	–[c]	0	15.8	–[c]	7.9
'Little Ice Age'	550–50	100	100	100	100	100
El Chicon[b]	691–687	0	1.3	0.1	0.18	0.4
Kuwae[b]	500–496	5.1	0.2	0	5.1	2.6
Huaynaputina[b]	350–346	6.8	0.4	0	3.8	2.8

Ages of volcanic eruptions (Zielinski, 2000) include the 5 years following each eruption. a, solar minimum; b, volcanic eruption, c, core pre- or post-dates event.

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